

Precision tests with $K_{\ell 3}$ and $K_{\ell 2}$ decays

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Abstract.

The analysis made in 2000 indicated that the unitarity relation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ might be broken at the 2.3σ level. At that time, however, $|V_{us}|$ was inferred from old experimental data. Since then, a great experimental and theoretical effort has been invested to understand the source of that discrepancy. Thanks to the new and improved measurements by BNL-E865, KLOE, KTeV, ISTRA+ and NA48, the old $K_{\ell 3}$ decay rate got shifted so that the new $|V_{us}|$ is now consistent with unitarity. On the theory side, much progress in the lattice QCD has been made in order to tame the systematic uncertainties related to the computation of the $K_{\ell 3}$ form factors.

This joint progress allowed to assess the validity of the CKM unitarity relation at the level of less than 1%. The key challenge of the future lattice studies will be to simulate lighter pions in the region in which ChPT predictions apply. Also interesting is the recent progress in accurately computing the kaon and pion decay constants on the lattice, which then give us access to $|V_{us}|$ and $|V_{ud}|$ from the corresponding leptonic decays.

In addition, we discuss that the $K_{\ell 3}$ and $K_{\ell 2}$ decays offer the possibility to test various scenarios of physics beyond Standard Model.

1. Introduction

From the experimental information on down- to up- quark transitions (such as $d \rightarrow u$, $s \rightarrow u$ and $b \rightarrow u$), we accede the effective dimension-six operators of the form, $D\Gamma_1 U \ell \Gamma_2 \nu$, with D (U) being a generic “down” (“up”) flavor, and $\ell \in \{e, \mu, \tau\}$. Their effective coupling G_{UD}^2 can be parametrized as the Standard Model (SM) contribution, $G_F^2 |V_{UD}|^2$, plus a possible new physics terms, $G_F^2 \epsilon_{NP}$. Since the dimension-six operators are not protected by gauge invariance the possible effects of non-decoupling are proportional to $(1 + M_W^2/\Lambda_{NP}^2)$. The effects of these non-standard contributions cannot be very large, but they can become detectable in high-precision experiments.

A convenient strategy to measure these effects against the SM parameters, G_F^2 and $|V_{UD}|$, is to test the Cabibbo universality hypothesis (or the unitarity constraint) between quark and lepton:

$$G_{CKM}^2 = G_\mu^2, \quad [\text{or } |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1, \text{ and } G_F \equiv G_\mu] \quad , \quad (1)$$

where $G_{CKM}^2 = G_{ud}^2 + G_{us}^2 + G_{ub}^2$, and $G_\mu = 1.166371(6) \times 10^{-5} \text{GeV}^{-2}$ is G_F , as measured from the accurate value of the muon lifetime [2].

We report on the progress related to the verification of the unitarity relation (1), particularly emphasizing the progress in taming the underlying hadronic uncertainties. As we shall see

¹ On behalf of the Kaon working group activity - Flavianet. The web-page [1] is steadily updated.

the CKM unitarity relation (1), is tested at the 1 % level (and even less), which therefore becomes an important constraint for beyond SM physics scenarios. For example, in SO(10) grand unification theories, the CKM unitarity relation (1) can be used to set the bound on the mass of Z' , namely $m_{Z'} > 1.4$ TeV, which is more than competitive with the one set through the direct collider searches, $m_{Z'} > 720$ GeV [3]. The unitarity also provides a useful constraint in various supersymmetry breaking scenarios [4].

In what follows, I discuss the present status of $|V_{us}|$, as obtained from the studies of semileptonic ($K_{\ell 3}$) and leptonic ($K_{\ell 2}$) decays. I will mainly concentrate on the theoretical progress. For the experimental novelties the reader is encouraged to consult the other contributions of the Flavianet Kaon Working group [1, 5–7]. I will also present some prospects for making the new physics searches from $K_{\ell 2}$ decays.

2. $|V_{us}|$ and the CKM test: $K_{\ell 3}$

In the SM, we deal with the following master formulas for $K_{\ell 3}$ and $K_{\ell 2}$ decay rates:

$$\Gamma(K_{\ell 3}(\gamma)) = \frac{G_\mu^2 M_K^5}{128\pi^3} C_K S_{\text{ew}} |V_{us}|^2 f_+(0)^2 I_K^\ell(\lambda_{+,0}) \left(1 + \delta_{SU(2)}^K + \delta_{\text{em}}^{K\ell}\right)^2, \quad (2)$$

$$\frac{\Gamma(K_{\ell 2}^\pm(\gamma))}{\Gamma(\pi_{\ell 2}^\pm(\gamma))} = \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(\frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2} \right) \times (1 + \delta_{\text{em}}), \quad (3)$$

where $C_K = 1$ (1/2) for the neutral (charged) kaon decay. $I_K^\ell(\lambda_{+,0})$ is the phase space integral which also includes the integration of the shape of the form factors parametrized by $\lambda_{+,0}$. The universal short-distance electromagnetic correction, $S_{\text{ew}} = 1.0232(3)$, has been computed in ref. [8], while the long-distance electromagnetic corrections $\delta_{\text{em}} = 0.9930(35)$ and $\delta_{\text{em}}^{K\ell}$, as well as the isospin-breaking ones, $\delta_{SU(2)}^K$, have been computed in refs. [9, 10] (see table 1 for $\delta_{\text{em}}^{K\ell}$ and $\delta_{SU(2)}^K$). The remaining quantities, $f_+(0)$, the vector form factor at zero momentum transfer

	$\delta_{SU(2)}^K$ (%)	$\delta_{\text{em}}^{K\ell}$ (%)
K_{e3}^+	2.36(22)	+0.08(15)
K_{e3}^0	0	+0.57(15)
$K_{\mu 3}^+$	2.36(22)	-0.12(15)
$K_{\mu 3}^0$	0	+0.80(15)

Table 1. Summary of the isospin-breaking factors [10]

$[q^2 = (p_K - p_\pi)^2 = 0]$, and f_K/f_π , the ratio of the kaon and pion decay constants, encode the non-perturbative QCD information on the flavor SU(3) breaking effects arising in the relevant hadronic matrix element.

This year, values of all the branching ratios of both neutral and charged $K_{\ell 3}$ decay modes from the new kaon experiments became available [11]. When translated into the uncertainty in $|V_{us}|f_+(0)$, it is only 0.4% for the charged modes and 0.1% for the neutral ones [5]. Averaged, that uncertainty is about 0.2%, which leads us to $|V_{us}|f_+(0) = 0.21666(48)$.

For the time being, such a highly precise measurement could not be translated to a similar error on the $|V_{us}|$ determination. The obstacle is obviously the difficulty to keep the theoretical uncertainties in $f_+(0)$ at the per-mil level. In eq.(2), $f_+(0)$ is defined in the absence of electromagnetic corrections and of the isospin-breaking terms. It is solely due to the strong interactions, described by non-perturbative QCD. In the flavor SU(3) limit it is merely equal to unity thanks to the conservation of the vector current. Its deviation from that limit is conveniently written as

$$f_+(0) = 1 + f_2 + f_4 + \dots \quad (4)$$

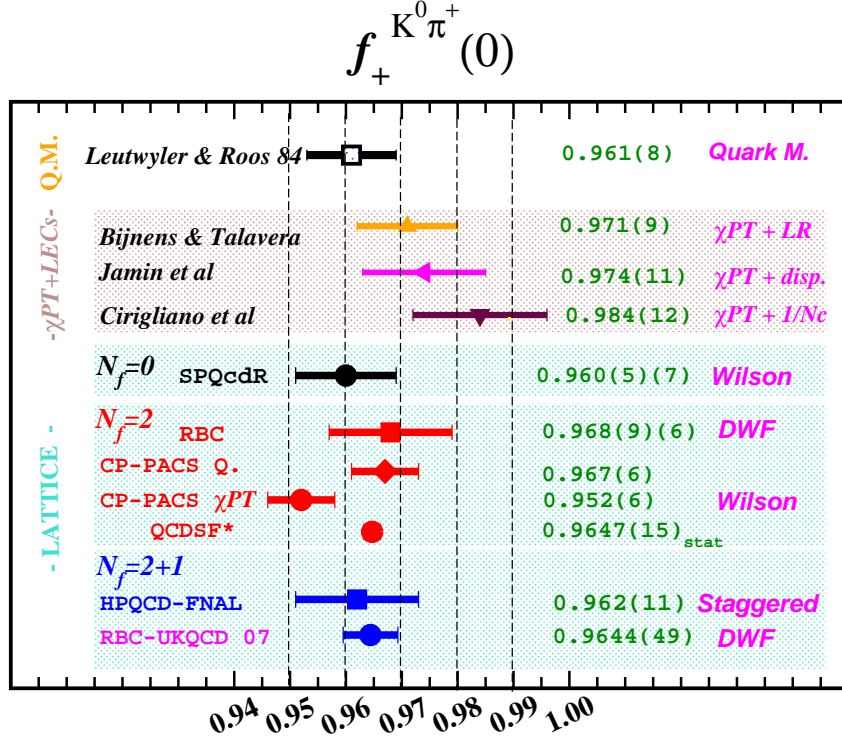


Figure 1. Current situation with the theoretical estimates of $f_+(0) \equiv f_+^{K^0\pi^-}(0)$ [12, 14–16]. Each method is being used to evaluate f_4 in eq. (4), while $f_2 = -0.023$ is predicted in ChPT, in terms of Kaon and pion masses only.

In chiral perturbation theory (ChPT) f_2 and f_4 are the leading and next-to-leading chiral corrections respectively. Ademollo–Gatto theorem ensures that the term $\propto (m_s - m_u)$ is absent and thus $f_2 = -0.023$ is an unambiguous prediction of ChPT. The calculation of the chiral loop contribution, $\Delta(\mu)$ in

$$f_4 = \Delta(\mu) + f_4^{\text{loc}}(\mu), \quad (5)$$

has been recently completed in ref. [13], but the full determination of f_4 necessitates an accurate estimation of the local counter-term $f_4^{\text{loc}}(\mu)$, which is $\mathcal{O}(p^6)$. Basically, over the years two theoretical approaches have been used. In one method, $f_4^{\text{loc}}(\mu)$ of eq. (5) is estimated by QCD models such as dispersion relation, $1/N_c$ limit and resonance saturation, whereas in the latter the full f_4 is estimated by Lattice QCD. All results (see fig.1) essentially confirm the old estimate made by Leutwyler and Roos which was obtained in a simple quark model [12]. The benefit of new results, obtained using more sophisticated approaches, lies in the fact that we are nowadays in the position to control the systematic uncertainties of our calculations while with the quark models this is not possible. To stress the importance of the accurate determination of f_4 , we should remind the reader that the experimental error on $|V_{us}|f_+(0)$ is only 0.2%, whereas the spread of theoretical estimates of $f_+(0)$ is still at the 1% \div 2% which is unsatisfactory. Recent progress in lattice QCD gives us more optimism as far as the prospects of reducing the error on $f_+(0)$ to well below 1% are concerned [17]. Most of the currently available results obtained by using lattice QCD worked with “heavy pions”. One may notice that the lattice QCD results are lower than those obtained by the ChPT-inspired models. An important step to improve the accuracy of $f_+(0)$ estimates has been recently made by the UKQCD-RBC collaboration [14]. Their preliminary result, $f_+(0) = 0.964(5)$ is obtained from the unquenched study with $N_F = 2 + 1$ flavors of quarks which have good chiral properties on the lattice (so

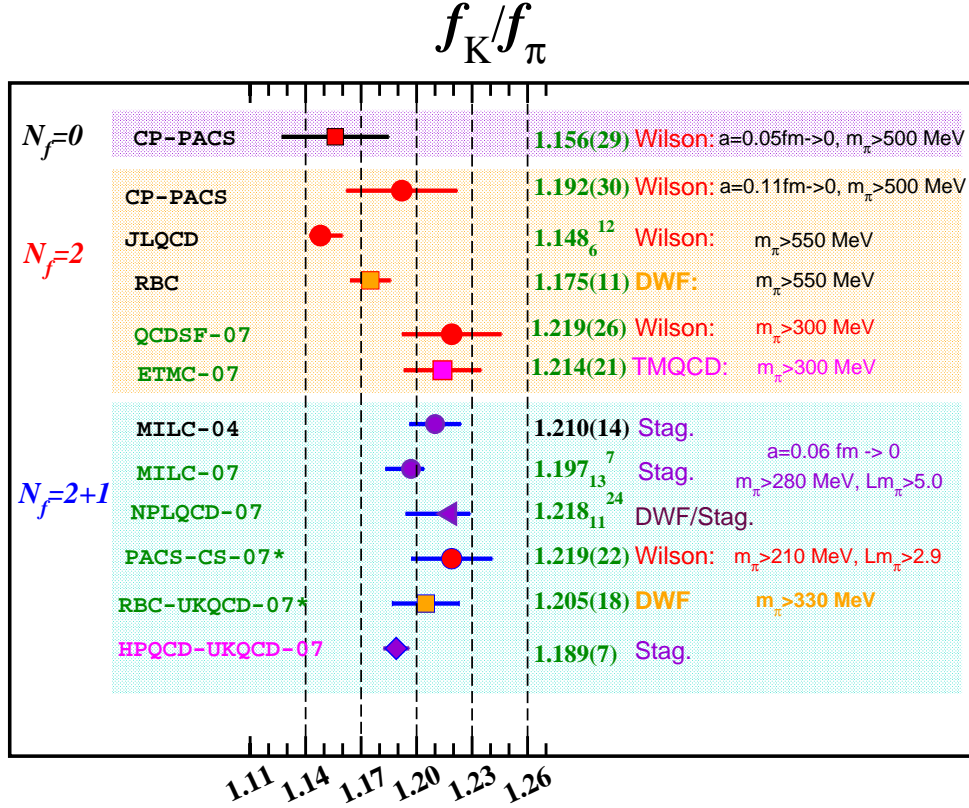


Figure 2. Summary of f_K/f_π estimates [19–23]. All values are from Lattice QCD. Recent results relied on the use of ChPT expressions to extrapolate to the physical limit.

called, Domain Wall quarks), and their pions ($\gtrsim 330\text{ MeV}$) are lighter than those reported in previous lattice QCD studies. Their overall error is estimated to be 0.5%, which is very encouraging. It is important to emphasize that they observe a mass dependence similar to that of f_2 . That is something new with respect to previous lattice studies (this is likely due to the fact that they work with lighter pions). One should keep in mind, however, that their result is obtained from the simulation at a single value of the lattice spacing (i.e. $a = 0.12\text{ fm}$) and in a relatively small extension of the fifth dimension of the lattice box². If the RBC-UKQCD estimate, $f_+(0) = 0.964(5)$, is combined with the experimental average, $|V_{us}|f_+(0) = 0.21666(48)$ [1], one gets that the CKM unitarity is confirmed to a precision well below 1% (see fig. 3), which is a new result.

A complementary research to provide the accurate estimate of $|V_{us}|$ is made through the $K_{\ell 2}$ decays. The most important mode is $K^+ \rightarrow \mu^+ \nu$ which has been recently updated by KLOE, so that the relative uncertainty is now 3%. To minimize the hadronic uncertainties, in eq. (3) we have introduced the ratio $\Gamma(K^+ \rightarrow \mu^+ \nu)/\Gamma(\pi^+ \rightarrow \mu^+ \nu)$. In this case, the QCD uncertainty enters with

$$f_K/f_\pi = 1 + r_2 + \dots \quad (6)$$

In contrast to the semileptonic decay discussed above, the Ademollo–Gatto theorem does not apply in this case and r_2 is not predicted unambiguously in ChPT. Instead one should fix the low energy constants from, say, the lattice QCD studies of f_K/f_π . This year many new results

² Even though $m_\pi L \gtrsim 4.5$, simulations with a larger fifth dimension, L_s would help because the mass of lightest quark ($= 0.005$ in lattice units) is very close to the residual mass parameter ($= 0.003$, also in lattice units). This is, in particular, relevant for f_K/f_π , which is the order parameter of the chiral symmetry.

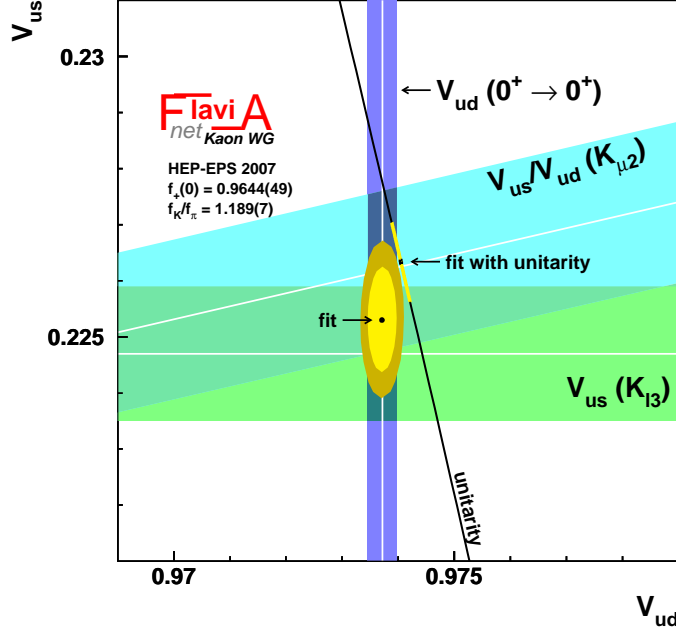


Figure 3. Summary of CKM unitarity test. To study the impact of high-precision lattice data, we use $f_+(0) = 0.964(5)$ [14] and $f_K/f_\pi = 1.189(7)$ [20] and we obtain $V_{ud}^2 + V_{us}^2 - 1 = 0.0011(7)$. As discussed in the text, all the lattice groups are currently working to reduce the remaining systematic uncertainties.

with either $N_F = 2$ and $N_F = 2 + 1$ dynamical quarks and rather light quark masses have been presented [19–23]. Such obtained values are summarized in fig. 2 from which we deduce that the present overall accuracy is about 1%. Note in particular the new lattice results with $N_F = 2 + 1$ dynamical quarks and pions as light as 280 MeV [19,20], obtained by using the so-called staggered quarks³ in which they covered a broad range of lattice spacings (i.e., $a = [0.06, 0.15]$ fm) and kept sufficiently large physical volumes (i.e., $m_\pi L \gtrsim 5.0$). It should be stressed, however, that the sensitivity of f_K/f_π to the lighter pions is larger than in the computation of $f_+(0)$, and that the chiral extrapolations are much more demanding in this case⁴. Notice also that at Lattice 2007 preliminary studies with $N_F = 2 + 1$ clover quarks and pion masses $\gtrsim 200$ MeV have been presented from either PACS-CS Collaboration [23] and ref. [25]. With respect to the results obtained with staggered quarks, the PACS-CS value of f_K/f_π in fig. 2 is restricted to a

³ Staggered fermions come in four tastes on the lattice. In the continuum limit the extra degrees of freedom decouple from physical predictions. But, at finite lattice spacing, where the data are produced, the taste symmetry is violated and this doublers are removed by hand, namely by taking the fourth root of the staggered quark determinant. Theoretically, this procedure has been only confirmed in perturbation theory and is currently a subject of controversies within the lattice QCD community [24]. Since the staggered dynamical quarks are computationally cheap, the first results with $N_F = 2 + 1$ have been produced by this approach. Thanks to recent progress in algorithm building [18], a safer and hopefully competitive alternatives are possible.

⁴ In some details, effects of chiral logs are not clearly disentangled and analytic terms (NNLO or NNNLO) are still needed in order to extrapolate from the simulated sea quark masses (such as $m_\pi \gtrsim 280$ MeV) to the physical point. For example, the two studies of ref. [19] and of ref. [20] with staggered quarks share the same configurations, but they differ in how to extrapolate to the physical masses. In the end, this implies a discrepancy for the central values of f_K/f_π from the two analysis, (namely, $f_K/f_\pi = 1.197_{13}^7$ and $f_K/f_\pi = 1.189(7)$ from ref. [19] and ref. [20] respectively). In any case, once we symmetrise the error of f_K/f_π in [19], we have $f_K/f_\pi = 1.194(10)$ and the two values looks now in good agreement. On the other hand, highly improved staggered fermions (HISQ) used in [20] for the valence quarks are designed to reduce the taste violation effects, which also should reduce the overall systematic uncertainty.

single lattice spacing ($a = 0.09$ fm) and relatively small physical volume ($m_\pi L \gtrsim 2.9$) [26]. For ref. [25], the final analysis is to be completed.

From the present knowledge of f_K/f_π , we see in fig. 3 that $|V_{us}|$ from $K_{\ell 2}$ is in agreement with unitarity too.

3. Future perspectives

Here we briefly summarize the probable perspectives of the $K_{\ell 3}$ and $K_{\ell 2}$ studies.

The lepton-universality searches in $R_K = \Gamma(K \rightarrow \mu\nu)/\Gamma(K \rightarrow e\nu)$, could give us some precious hints on new physics scenarios. On one hand, R_K can be predicted to 0.04 % accuracy in the SM, while on the other hand the Higgs contributions $[\propto (s_R u_L)(e_R \nu_L^\tau)]$, arising from lepton violating couplings at large $\tan\beta$, can give an effect $\sim 1\%$ [29]. Recent measurements of this ratio by NA48 [30] and KLOE [31] reached a percent level of accuracy which makes it very exciting to see what the NA60 [30] experiment will achieve as they aim at lowering the uncertainty to the per-mil level.

A possible deviation of $|V_{us}|_{K_{\ell 3}}/|V_{us}|_{K_{\ell 2}}$ from unity, as argued in some models of physics beyond SM, represents another exciting avenue for the future searches [27, 28]. Notice that in this case the hadronic uncertainties enter through $(f_K/f_\pi)/f_+(0)$, which will hopefully be reduced by the future lattice QCD studies with ever lighter pions, as mentioned in the previous section. Moreover, it would be particularly interesting to compute directly $(f_K/f_\pi)/f_+(0)$ on the lattice, i.e., in the same set of simulations ⁵.

Before the lattice study of $(f_K/f_\pi)/f_+(0)$ is made, its value can be obtained by using the Callan-Treiman formula,

$$f_0(m_K^2 - m_\pi^2) = \frac{f_K/f_\pi}{f_+(0)} + \text{“corrections } \mathcal{O}(10^{-3})\text{”} \quad , \quad (7)$$

and the experimental information on the scalar form factor, $f_0(q^2)$. This involves an extrapolation of the scalar form factor from the physical region $0 < q^2 < (m_K - m_\pi)^2$ to $q^2 = m_K^2 - m_\pi^2$ which can be made by using an appropriate dispersion relation, as proposed in ref. [28]. Experimental groups are now implementing this new parametrization and the results are expected soon [32–35]. This would not only provide an important cross-check of lattice QCD estimates, but would also help improving the bound on coupling to the right-handed currents [28] and/or scalar operators [27].

4. Conclusions

Besides a few clean observables [29], future progress in leptonic and semileptonic kaon decays will mainly rely on the improvements in lattice QCD. It should be emphasized that over the past few years a tremendous progress in lattice QCD has already been achieved. Most notably the quenched approximation has been removed. However, for the precision which we would like to have, much effort is still needed. It is essential to have light sea quarks in order to match with the ChPT regime, while keeping the discretisation and finite volume effects under control and below 1% too.

5. Acknowledgments

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⁵ In particular, since the advanced status of staggered simulations, it would be interesting to improve the very preliminary analysis of $f_+(0)$ in [15].

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